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14. ABSTRACT

For elements of an infinite planar array, fundamental upper bounds on the impedance matching bandwidth are investigated. Planar arrays in free space, those over a conducting ground plane, and those on a grounded dielectric substrate are considered. For free-space arrays, the bounds are based on the forward scattering sum rule for doubly periodic arrays. For conductor-backed arrays, they are based on the low-frequency expansion of the plane-wave reflection coefficient, following Fano's approach for deriving bandwidth bounds of matching networks, but applied to a scattering configuration. In both cases, the bandwidth upper bounds are expressed in terms of both geometrical

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Report Title

Final Report: Fundamental Limitations of Phased Array Antenna Elements

ABSTRACT

For elements of an infinite planar array, fundamental upper bounds on the impedance matching bandwidth are investigated. Planar arrays in free space, those over a conducting ground plane, and those on a grounded dielectric substrate are considered. For free-space arrays, the bounds are based on the forward scattering sum rule for doubly periodic arrays. For conductor-backed arrays, they are based on the low-frequency expansion of the plane-wave reflection coefficient, following Fano's approach for deriving bandwidth bounds of matching networks, but applied to a scattering configuration. In both cases, the bandwidth upper bounds are expressed in terms of both geometrical (e. g., unit cell dimensions) and electrical (e.g., scan angle, low-frequency polarizabilities) design parameters. Quantitative relations are revealed to find that the bandwidth bounds increase with stronger polarizabilities and smaller cell dimensions. Strong coupling between neighboring elements helps increase the bandwidth via increased polarizability values compared with their isolated counterparts. For conductor-backed arrays, higher-order bandwidth bounds are identified and they include the exact effect of the element design unlike previously known bounds. In addition, the infinite planar array counterparts of the vector effective height and the receiving area of a receiving antenna are found.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/17/2014	7.00	Do-Hoon Kwon, David M. Pozar. Energy Storage and Radiation Q of InfinitePlanar Dipole Phased Arrays, IEEE Transactions on Antennas and Propagation, (01 2014): 153. doi:
08/19/2013	3.00	Yong Heui Cho, Do-Hoon Kwon. Efficient Mode-Matching Analysis of 2-D Scattering by Periodic Array of Circular Cylinders, IEEE Transactions on Antennas and Propagation, (03 2013): 1327. doi: 10.1109/TAP.2012.2227661
12/08/2015	14.00	Do-Hoon Kwon, Hsieh-Chi Chang. Bandwidth limitations of linearly polarized infinite planar phased arrays in free space, IEEE Trans. on Antennas and Propagation, (08 2015): 3423. doi:
12/08/2015	13.00	Do-Hoon Kwon. Effective height, receiving area, and receiving efficiency of infinite planar phased array elements, IEEE Trans. on Antennas and Propagation, (05 2015): 2022. doi:
TOTAL:	**4**	

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received   Paper

08/19/2013   5.00   Do-Hoon Kwon, David M. Pozar. Energy Storage and Radiation Q of Infinite Planar Phased Arrays,
, (06 2013): 0. doi:

TOTAL: **1**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

08/26/2013 6.00 Do-Hoon Kwon. Bandwidth Limitations of Phased Array Elements,
              2013 IEEE International Symposium on Antennas and Propagation. 07-JUL-13, . : ,

08/27/2014 9.00 Do-Hoon Kwon, David M. Pozar. Radiation Q of Planar Dipole Phased Arrays on a Grounded Substrate,
              2014 IEEE Antennas and Propagation Society International Symposium. 06-JUL-14, . : ,

08/29/2014 12.00 David M. Pozar, Do-Hoon Kwon. Radiation Quality Factor Analysis of Planar Phased Arrays,
              2013 IEEE International Symposium on Phased Array Systems & Technology. 15-OCT-13, . : ,

12/08/2015 15.00 Do-Hoon Kwon. Received voltage and power for an arbitrary element of infinite planar arrays,
              2015 IEEE International Symposium on Antennas Propagation. 19-JUL-15, . : ,

   TOTAL: **4**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>   <u>Paper</u>

01/17/2014 8.00 Do-Hoon Kwon, David M. Pozar. Radiation Q of Planar Dipole Phased Arrays on a Grounded Substrate,
              IEEE International Symposium on Antennas and Propagation (01 2014)

02/25/2013 1.00 Do-Hoon Kwon. Bandwidth Limitations of Phased Array Elements,
              IEEE International Symposium on Antennas and Propagation (01 2013)

02/25/2013 2.00 Yong Heui Cho, Do-Hoon Kwon. Efficient Mode-Matching Analysis of 2-D Scatteringby Periodic Array of
              Circular Cylinders,
              IEEE Transactions on Antennas and Propagation (06 2012)

08/19/2013 4.00 David M. Pozar, Do-Hoon Kwon. Radiation Quality Factor Analysis of Planar Phased Arrays,
               (06 2013)

08/27/2014 10.00 Do-Hoon Kwon. Receiving Properties of Infinite Planar Phased Arrays,
              IEEE Transactions on Antennas and Propagation (07 2014)

08/28/2014 11.00 Do-Hoon Kwon, Hsieh-Chi Chang. Bandwidth Limitations of Infinite Planar Phased Arrays in Free Space,
              IEEE Transactions on Antennas and Propagation (08 2014)

   TOTAL: **6**

Number of Manuscripts:

Books

Received   Book

TOTAL:

Received   Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Hsieh-Chi Chang	0.86	
Caglar D. Emiroglu	0.24	
Amin Nikravan	0.04	
FTE Equivalent:	**1.14**	
Total Number:	3	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Do-Hoon Kwon	0.13	
FTE Equivalent:	**0.13**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Mark Page	0.10	Electrical Engineering
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

1. Theory on the receiving properties of infinite planar array elements

For the first time, the array element counterparts of the vector effective height and receiving area of an isolated antenna were expressed in terms of the transmitting properties of the same array. The Lorentz reciprocity theorem was used to relate the element's received open-circuit voltage and the power delivered to the load with the transmitting performance descriptors.

The vector effective height for an array element is defined such that an inner product between the effective height and the incident electric field vector produces the complex open-circuit voltage of the element in the frequency domain, as is the case for the open-circuit received voltage of an isolated antenna. Similarly to an isolated antenna, the element effective height describes both the polarization and element pattern characteristics of the array.

A new directivity quantity, named the element Floquet directivity, was introduced to describe the bidirectional or unidirectional nature of radiation under any given scan condition. Symmetric bidirectional and complete unidirectional radiation characteristics correspond to the Floquet directivity value of unity and two, respectively. The exact expression for the receiving area of an element was derived for the first time. The contributing factors were found to be the radiation efficiency, polarization and impedance mismatch factors, and the Floquet directivity together with the projected element cell area in the scan direction.

They represent theoretical establishment of the receiving properties of planar arrays in terms of transmitting performance parameters for the first time.

2. Derivation of fundamental bandwidth bounds for free-space arrays

For elements of infinite planar arrays in free space, fundamental upper bounds on the element matching bandwidth were derived based on the forward scattering sum rule for an array of doubly periodic scatterers. The analyticity of the forward scattering, or transmitting, coefficient in the lower half of the complex wavenumber plane was exploited to relate an integrated extinction cross section over frequency to the static scattering properties of the element under periodic boundary conditions. Quantitative element bandwidth bounds were found in terms of the strengths of the induced electric and magnetic dipole moments, taking into account of the coupling effects between neighboring elements. For both resonant narrowband and ultrawideband responses, the bandwidth upper bounds were expressed in terms of geometrical (unit cell dimensions, scan angle, polarizabilities) as well as electrical (radiation efficiency, polarization mismatch factor, Floquet directivity, polarizabilities) design parameters. Tight bandwidth limits were found by using the generalized absorption efficiency value of 0.5.

Quantitative bandwidth bounds revealed that smaller unit cell dimensions and strong induced dipole moments increase the bandwidth upper bound.

3. Higher-order Fano matching bandwidth bounds for conductor-backed planar array elements

For more practical planar arrays backed by a planar conducting ground plane, higher-order bandwidth bounds were found based on the plane-wave reflection coefficient in a receiving/scattering configuration for different scan conditions and element compositions. The reflection coefficient was expanded in terms of the wavenumber in the low-frequency range and the fact that such a reflection coefficient represents a causal system response, making it analytic in the lower-half of the complex wavenumber plane. Subsequently, the classical Fano analysis is applied and integral equalities involving the magnitude of the reflection coefficient were derived. Previously known results use the lowest-order integral identity to find the bandwidth upper bound. However, expressions of the existing bounds do not involve details of the element design, significantly reducing their utility in practical array designs. In this project, a higher-order integral identity based on the expansion including the next-higher order term was derived, which provides an additional requirement for the magnitude of the reflection coefficient to satisfy. It is found that the resulting bound depends the specific element antenna design, expressed in terms of the low-frequency electric and magnetic polarizabilities. Inspection of the higher-order bandwidth bounds provides a promising element design strategy for approaching the newly established bounds.

Higher-order impedance matching bounds provide tighter bandwidth limits than previously known results. The exact functional dependence of the new higher-order bounds provides a physical insight into increasing the bandwidth of practical planar phased array antennas.

Technology Transfer